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Heuristic Optimization Technique for CHP-Wind Power Dispatch

Vishal Chaudhary, Manjaree Pandit, Hari Mohan Dubey
Department of Electrical Engineering
Madhav Institute of Technology and Science
Gwalior (M.P) India
vishal.chaudhary30@yahoo.com; manjaree_p@hotmail.com; harimohandubeymits@gmail.com

Abstract— **This paper applies Differential Evolution (DE) for solving combined heat and power dispatch (CHP) problem with wind turbines. The CHP economic dispatch problem consist of two sub problems, namely, heat dispatch and power dispatch. The optimal dispatch utilization of multiple CHP units and wind turbines is a complicated problem due to the complex constraints such as feasible operating regions created by mutual dependence of heat and power. The uncertainty of wind speed and wind power is modeled using the Weibull probability distribution. Economic dispatch is carried out for cost optimization with varying wind power. The proposed method is able to handle all complex constraints very effectively without any violations. The developed optimization model is tested and validated on a study system from literature.**

Index Terms— **Combined heat and power dispatch, Differential Evolution, Weibull probability density function, Wind power, Heuristic Optimization.**

I. Introduction

Cogeneration or combined heat and power is simultaneous production of multiple forms of energy in a single process. The Federal Energy Regulatory Commission (FERC) in the US defined cogeneration as “the combined production of electric power and useful thermal energy by sequential use of energy from one cause of fuel”. The benefit of cogeneration is achieved mainly from utilization of energy, which is normally lost in condenser during the separate power production. By capturing the excess heat, CHP reaches an efficiency of up to 89%, compared with 55% for the best usual plants. This means that a smaller amount fuel needs to be consumed to produce the same amount of useful energy. It also contributes to emission reduction compared to systems with separate electric power and heat production [1].The primary objective of economic dispatch in a conventional power plant is to find the optimal power outputs of generating units such that the total demand matches the generation with minimum fuel cost. In Ref. [2] a stochastic model for optimal dispatch of CHP units along with wind power is carried out while treating harmful emissions as inequality constraints. In Ref. [3] a model of CHP dispatch is developed for a system consisting of both thermal generators and wind turbines. In this model, the chance of stochastic wind power is included in the constraint set and used the cross-product of power and heat terms, as well as two-dimensional polygons called feasible operation regions (FORs). Here Wind Power (WP) means the real electric power generated by wind turbines and not the input wind power. Evolutionary optimization methods are very popular among researchers due to their fast convergence; population based effective search mechanism and simplicity. The major issue with evolutionary techniques is to create a balance between global search and local search. Issues such as premature convergence, setting up optimal tuning parameters and finding optimal population size appear prominently in recent publications [4-6].One of the major advantage of wind energy is that, after the initial land and capital costs, there is basically no cost involved in the production of power from wind energy conversion systems(WECS).The primary feature that differentiates wind-powered from conventional generators in the economic dispatch problem is the stochastic nature of wind speed [7].Wind energy is an inexhaustible energy, which can be used to produce electricity without the use of fuel and can save fuel cost for the power system. But on the further hand, wind energy is indiscriminate, which increases the insecurity during the operation of power system and presents new challenges to the economical operation of power systems. In Ref. [8] the economic dispatch problem for power systems which contain wind power generation plants. In Ref. [9] an extension of Simulated Annealing algorithm is developed for the solution of wind–thermal coordination scheduling problem. A significant part of installed thermal generation consists of combined heat and power (CHP) units, which enforce additional constraints on unit commitment and dispatch due to heat-demand-driven operation [10].Wind is regarded as the most suitable renewable energy resource for bulk power generation and the best alternative to the conventional energy resources mainly because of the increased capacities of wind turbine generators that are available [11].The benefits of CHP and WP have been well known inside and outside the power engineering society[12].In Ref. [13] the problem of economic optimal operation of CHP system consisting of wind turbine, PV, fuel cell, waste heat boiler, gas boiler, battery, thermal and electric load is used. A plant growth simulation algorithm has been applied for optimal generation scheduling of power system having coal fired units and wind farm [14]. In place of traditional fossil fuel based power units the present trend is to incorporate non-conventional power generation through microgrid. Economic deployment of CHP based distributed energy resources considering cost as well as emission minimization is proposed using DE [15]. Electric heat pumps (EHP) can provide space heating in the domestic sector [16]. In Ref. [17] the effect of short duration wind generation variation on

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optimal load dispatch is considered. DE is designed for dynamic economic dispatch model including wind energy [18].

II. The Ed Model With Chp-Wind

In this section, we establish an ED-CHP model characterized by the probability distribution. First, we define p_a to be the tolerance that the total demand P_d cannot be satisfied. For example, if $p_a = 0.1$, then up to 10% of the chance of insufficient supply could be tolerated. Therefore, a larger p_a implies more tolerance toward inadequate supply, and vice versa. Secondly, the model will take the transmission loss into account. For convenience of presentation, in the following, Total sum of total power demand (P_d) and total transmission losses (P_s) is given by:

$P_{ds} = P_d + P_s$

$$= P_d + \sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij}\, cp_i\, cp_j + \sum_{i=1}^{n} B_{0i}\, cp_i + B_{00} \tag{1}$$

Where B_{ij} is the parameters of transmission losses, cp_i is the power generated by generator i, cp_j is the power generated by generator j.

With these notations, the ED-CHP model takes the following form:

minimize

$$z = \sum_{i=1}^{n}(q_{i2}\, cp_i^2 + q_{i1} cp_i + q_{i0} + h_{i2} ch_i^2 + h_{i1} ch_i + h_{i0}\, cp_i\, ch_i) \tag{2}$$

subject to

$$P_r\left(W + \sum_{i=1}^{n} cp_i \le P_{ds}\right) \le p_a \tag{3}$$

Here q_{i0},q_{i1},q_{i2} are the Power cost coefficients of generator i and P_r is the probability, the coefficients h_{i0}, h_{i1},h_{i2} are the heat cost coefficients of generator i and z is Cost index in the ED-CHP model.

Heat generated by the generator i is given by

$$\sum_{i=1}^{n} ch_i = H_d \tag{4}$$

Where H_d is the total heat demand

$$A_{for}\begin{bmatrix} cp \\ ch \end{bmatrix} \le b_{for}, \tag{5}$$

$$cp_{min,i} \le cp_i \le cp_{max,i}\ ,\ ch_{min,i} \le ch_i \le ch_{max,i} \tag{6}$$

Here i=1, 2,……, N represents number of generating units and A_{for} is the 2N × 2N coefficient matrix of feasible operation region (FOR), b_{for} is the 2N ×1 coefficient vector of FOR, cp is the N ×1 vector of power generation, ch is the N ×1 vector of heat output of generating units,, W represents all wind power (WP) to be dispatched. Since the total WP is characterized by a single random variable here, it implies that all wind turbines are located in a coherent geographic area, represented by a small wind farm or a cluster of turbines in a large wind farm. Otherwise, more than one random variable should be included in the model.

Constraint (4) can be rewritten as:

$$F_W\left(P_{ds} - \sum_{i=1}^{n} cp_i\right) = P_r\left(W \le P_{ds} - \sum_{i=1}^{n} cp_i\right) \le p_a \tag{7}$$

Here F_W is the Cumulative distribution function of random variable W and p_a is the upper bound of probability that the sum of real power not greater than P_{ds}.

It should be mentioned that the value of p_a must satisfy the following relation:

$$P_r\,(W{=}0) < p_a < 1. \tag{8}$$

This is because, if $p_a \le P_r$ (w=0), then the feasible region induced by (4) is $\sum_{i=1}^{n} cp_i \ge P_{ds}$ which implies that no WP would be pursued. Furthermore, $p_a < 1$ since p_a is a threshold of probability.

$$P_r\left(W \le P_{ds} - \sum_{i=1}^{n} cp_i\right) \tag{9}$$

$$= 1 + \exp[-(\frac{v_{out}}{c})^k]$$

$$- \exp\{-\frac{1}{w_r^k c^k}[v_{in} w_r + (v_r - v_{in})(P_{ds} - \sum_{i=1}^{n} cp_i)]^k\} \le p_a$$

Here v_r, v_{in},v_{out} are the rated, cut-in, and cut-out wind speeds, c is the Scale factor of the Weibull distribution, and k is the Shape factor of the Weibull distribution

The above inequality can be easily converted into the following expression:

$$\sum_{i=1}^{n} cp_i \ge P_{ds} + \frac{v_{in} w_r}{v_r - v_{in}}$$

$$- \frac{w_r c}{v_r - v_{in}}\{-\ln[1 + \exp\left(-\frac{v_{out}^k}{c^k}\right) - p_a]\}^{\frac{1}{k}}$$

$$= P_{ds} + \frac{v_{in} w_r}{v_r - v_{in}} - \frac{w_r c}{v_r - v_{in}} |\ln[1 + \exp\left(-\frac{v_{out}^k}{c^k}\right) - p_a]|^{\frac{1}{k}}$$

$$= P_{ds} - w_r h_p\ ; \tag{10}$$

Here w_r: Rated power of the WP generating unit.

Where Intermediary parameter (h_p) is given by

$$h_p = \frac{c}{v_r - v_{in}} |\ln[1 + \exp\left(-\frac{v_{out}^k}{c^k}\right) - p_a]|^{\frac{1}{k}} - \frac{v_{in}}{v_r - v_{in}} \tag{11}$$

Therefore from (10) constraint (4) can be written as

$$\sum_{i=1}^{n} cp_i \ge P_{ds} - w_r h_p\ ; \tag{12}$$

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III. Stochastic Wind Power Model

Weibull distribution [19] is used for modeling the highly nonlinear relation between the wind power W and wind speed V (m/sec). It varies randomly with time and can be expressed in terms of the cumulative probability distribution function as:

$$F_V(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (v \geq 0) \tag{13}$$

Where c and k are the scale factor and shape factor, respectively. Correspondingly, the probability density function of V is:

$$f_v(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{14}$$

The relation between the input wind power and the output electric power depends on many factors, like the efficiencies of generator, wind rotor, gearbox, and inverter, depending on what kind of turbine is being employed. The generic relation between wind power and wind speed can be given as [20]:

W=

$$\begin{cases} 0; & (V < v_{in} \ or \ V \geq v_{out}) \\ w_r; & (v_r \leq V < v_{out}) \\ \dfrac{(V - v_{in})w_r}{v_r - v_{in}} & (v_{in} \leq V < v_r) \end{cases} \tag{15}$$

Where v_r , v_{in} , v_{out} : Rated, cut-in, and cut-out wind speeds; W is the power generated by the wind generating unit; Wr is the rated power of the wind generating unit; c is the scale factor and k is the shape factor of the Weibull distribution.

IV. Differential Evolution

Heuristic optimization techniques based on the principle of evolution have assumed marked popularity over the conventional methods of optimization, particularly for practical, constrained engineering problems. These methods are highly advantageous due to their powerful convergence characteristics and ability to generate feasible solutions for all kinds of problems. Differential evolution (DE) proposed by Storn and Price is a population based technique which uses random operators and real number. The DE algorithm employs a special differential operator to generate new solutions from the parent population in place of the classical crossover or mutation operators used in the well established genetic algorithm (GA) technique. The difference between two randomly selected parameter vectors is used to improve the population. The DE has three powerful stages named as mutation, crossover and selection.

A. Initialization phase

An initial population of feasible solutions is generated randomly to represent the search domain using the following expression.

$$X_j = X_j^{\min} + rand \times (X_j^{\max} - X_j^{\min}) \text{ for j=1,2....D} \tag{16}$$

Where D is the dimension of the population, *rand* is an operator which generates a random number between 0-1 and X^{min} and X^{max} are the minimum and maximum limits of the i^{th} variable. The j^{th} member of the D dimensional population vector of size R can be represented as

$$X_{ij} = [X_{i1}, X_{i2} \ldots\ldots X_{iD}] \text{ for i=1,2........R} \tag{17}$$

B. Mutation

The initial target population is employed to produce a mutant/donor vector as shown below.

$$Z_i(t+1) = X_{i,r1}(t) + F[X_{i,r2}(t) - X_{i,r3}(t)] \tag{18}$$

The mutant vector Z_i is formed using two random population members other than X_i. The mutation rate F controls the differential variation that is instrumental in creating a mutant population to avoid search stagnation. It is selected between 0-2. Selection of F has a significant effect on the performance of DE algorithm. A smaller mutation rate makes the algorithm slow and longer time will be taken for convergence. A large F provides high level of exploration, but may cause the algorithm to skip optimal solution. Actually, the value of F should be small enough to enable the algorithm to explore tight valleys and large enough to allow global exploration in order to maintain diversity. The optimal value of F can be found by trial and error.

The manner, in which the mutant vector is formed, depends on which DE scheme is employed. In this paper the mutation strategy known as DE/rand-to-best/1 as given below is found to perform the best.

$$Z_i(t+1) = x_i(t) + F[x_{i,best}(t) - x_i(t)] + F[x_{i,r1}(t) - x_{i,r2}(t)] \tag{19}$$

Here r_1 and r_2 are random integers (and not the same as the integer i) generated in the range 1-R

C. Crossover Operation

After the mutation operation is completed as explained above, the crossover operation is performed. In this operation some variables of the target vector *(X_i)* are replaced by the mutant vector *(Z_i)* to form the trial vector *(U_i)* using the following logic.

$$U_{ij}(t+1) = \begin{cases} Z_{ij}(t+1), \ldots .if(Num(j) \leq CR) or (j = randint(i)) \\ X_{ij}(t), \ldots\ldots .if(Num(j) > CR) or (j \neq randint(i)) \end{cases} \tag{20}$$

Where *Num (j)* is a random number generated for the j^{th} dimension and *CR* is a crossover rate selected in the range [0, 1].

D. Selection

Selection is an important step and plays a major role in producing better solution/offspring. To decide whether or not the trial vector should be a member of the population of the subsequent generation, it is compared with the corresponding target vector. The selection process for an objective function under minimization is carried out by comparing the cost of each trial vector $U_i(t+1)$ with that of its parent target vector $x_i(t)$ as follows:

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$$X_i(t+1) = \begin{cases} U_i(t+1)\ldots \; if \; (U(t+1)) < f(X_i(t)) \\ X_i(t) \ldots\ldots\ldots \quad otherwise \end{cases} \tag{21}$$

V. Numerical Results And Analysis

The CHP-wind model described by (2)-(6) a DE algorithm was developed in MATLAB environment. The constraints were handled by using penalty function approach. The algorithm was tested on a standard test function from literature [3] and the results are found to be better than the reported results.

A. Description of the Test System

The test system has two thermal /heat generating units and one wind farm. The cost calculation for unit one and two using coefficients for power and heat is given as C_1 and C_2.

$$C_1 = 0.1035 * cp_1^2 + 34.5011 * cp_1 + 2650.0312 + 0.02498 ch_1^2 + 2.2031 * ch_1 + 0.0510 * cp_1 * ch_1 \tag{22}$$

$$C_2 = 0.0435 * cp_2^2 + 36.0012 * cp_2 + 1250.0431 + 0.0270 ch_2^2 + 0.6002 * ch_2 + 0.0409 * cp_2 * ch_2 \tag{23}$$

The object is to minimize (C_1+C_2) subject to the unit operating limit constraints given by

$10 \le cp_1 \le 60$; $6 \le cp_2 \le 40$; $0 \le ch_1 \le 55$ and $0 \le ch_2 \le 30$

The FOR constraints of CHP units are given by

$$A_{for} = \begin{bmatrix} -1 & 0 & -4 & 0 \\ 3 & 0 & 14 & 0 \\ 19 & 0 & -8 & 0 \\ 0 & -7 & 0 & -20 \\ 0 & 1 & 0 & 3 \\ 0 & 5 & 0 & -2 \end{bmatrix}, \quad b_{for} = \begin{bmatrix} -80 \\ 840 \\ 680 \\ -240 \\ 120 \\ 90 \end{bmatrix}$$

These constraints given by (5) get converted into straight line boundaries and the enclosed region represents the FOR of the two units, given as

$$3cp_1 + 14ch_1 \le 840$$
$$19cp_1 - 8ch_1 \le 680$$
$$-7cp_2 - 20ch_2 \le -240$$
$$cp_2 + 3ch_2 \le 120$$
$$5cp_2 + -2ch_2 \le 90$$

Power Demand and Heat Demand are 80 MW and 70 MWth. The cut-in, cut-out and rated wind speeds are 5, 45 and 15 m/s respectively. The rated wind power is 20MW. Transmission losses are neglected in this study.

B. Effect of probability of wind power

The optimal dispatch of CHP units, i.e.power and heat is computed for different values of wind probability. The results are plotted in Table I. The results show that the cost of thermal units reduces with increasing wind probability. The Fig. 1 plots the relationship between probability and wind power for different values of shape factor. It can be seen that the wind power and wind reliability have a direct relation. Fig. 3 shows the stable convergence characteristics of the De algorithm for CHP-wind problem for different population sizes. The mutation and crossover rate in DE were taken as 0.8 and 0.7 respectively because best results were obtained at these values.

Table I. Optimal Solutions (K=1.5) (PD=80MW, HD=70 Mwth)

p_a	0.25	0.30	0.35	0.40	0.45	0.50	0.55
cp_1	47.1	45.1	43.1	41.0	38.9	36.7	34.4
ch_1	40.0	40.0	40.0	40.0	40.0	40.0	40.0
cp_2	30.0	30.0	30.0	30.0	30.0	30.0	30.0
ch_2	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Wind	2.8	4.9	6.9	8.9	11.0	13.2	15.5
Cost($/h)	7179.3	7086.4	6994.2	6901.2	6806.5	6709.1	6607.7
Power violation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heat violation	0.0	0.0	0.0	0.0	0.0	0.0	0.0

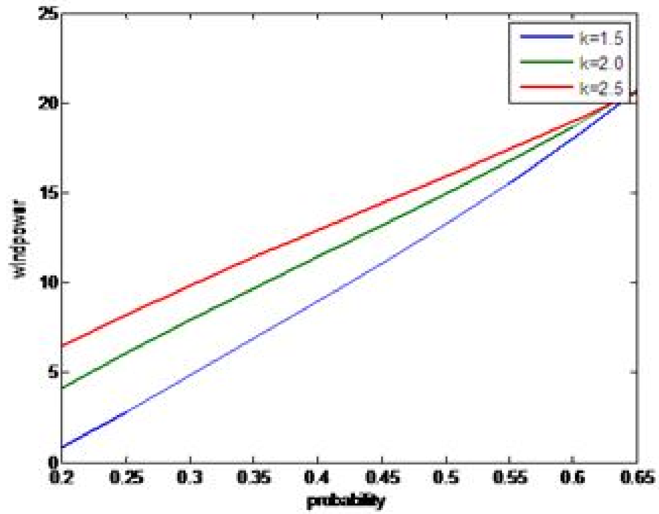

Figure 1. Variation of wind power with probability factor

C. Effect of shape factor

The shape factor k of Weibull distribution directly affects WP availability and hence cost of a wind-CHP system. Table I, II and III give the complete dispatch results of the test system for different values of shape factor. With increase in the value of shape factor the wind availability increases and therefore the cost of conventional power generation goes down. Fig. 2 shows the relation of generating cost and probability for different shape factors.

Table II. Optimal Solutions (K=2.0) (PD=80MW, HD=70 Mwth)

p_a	0.25	0.30	0.35	0.40	0.45	0.50	0.55
cp_1	43.9	42.0	40.3	38.5	36.8	35.0	33.1
ch_1	40.0	40.0	40.0	40.0	40.0	40.0	40.0
cp_2	30.0	30.0	30.0	30.0	30.0	30.0	30.0
ch_2	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Wind	6.0	7.9	9.6	11.4	13.1	14.9	16.8
Cost($/h)	7030.5	6947.6	6867.6	6789.3	6711.5	6633.2	6553.4
Power violation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heat violation	0.0	0.0	0.00	0.0	0.0	0.0	0.0

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TABLE III. OPTIMAL SOLUTIONS (K=2.5) (PD=80MW, HD=70 MWTH)

p_a	0.25	0.30	0.35	0.40	0.45	0.50	0.55
cp_1	41.7	40.1	38.5	37.0	35.5	34.0	32.5
ch_1	40.0	40.0	40.0	40.0	40.0	40.0	40.0
cp_2	30.0	30.0	30.0	30.0	30.0	30.0	30.0
ch_2	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Wind	8.2	9.8	11.4	12.9	14.4	15.9	17.4
Cost($/h)	6933.4	6859.1	6790.1	6723.1	6657.4	6592.3	6526.8
Power violation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heat violation	0.0	0.0	0.00	0.0	0.0	0.0	0.0

D. Constraint handling and convergence behavior

The idea behind the CHP-wind optimization is to utilize available wind generation and minimize the following function. The constants α and β are the power and heat penalty coefficients respectively. The second term imposes a penalty on the individual in terms of increased cost, if power balance constraint is not satisfied and the third term imposes a penalty, if heat balance constraint is not satisfied.

$$C_1 + C_2 + \alpha\left[\sum_{j=1}^{N} cp_j + WP - P_{DS}\right]^2 + \beta\left[\sum_{j=1}^{N} ch_j - H_D\right]^2 \tag{24}$$

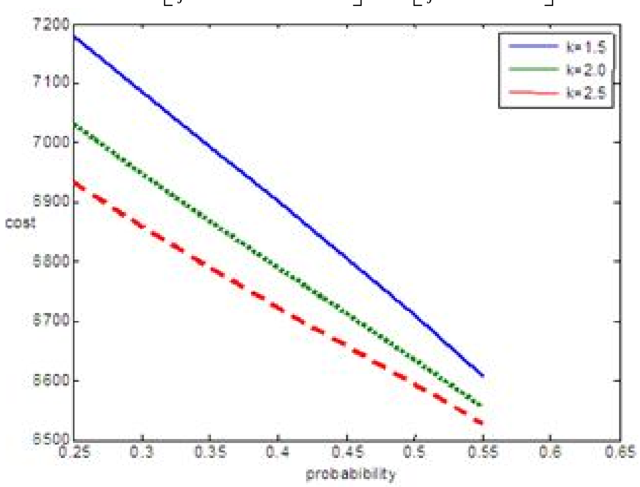

Figure 2. Variation of cost with wind probability factor

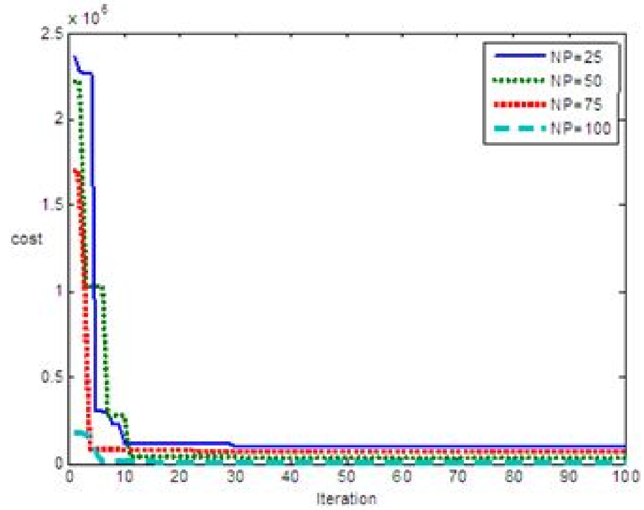

Figure 3. Convergence characteristics of DE method for wind-CHP plant

E.Comparision with Published results.

The results of the DE based proposed method for optimal CHP-Wind dispatch is compared with results from literature [3]. The results obtained by the proposed method are found to be very close to [3].Table IV presents the comparison of the two methods. The effect of Shape factor of the weibull distribution on cost of operation is studied. It is observe that as the value of k increases, the optimal cost decreases. For k=1.5 the cost was 7179 which reduces to 6933 when k=2.5. Similarly when the probability of wind power is increased the cost is found to reduce significantly.

CONCLUSIONS

The proposed method is capable of computing feasible results and the proposed algorithm has a stable convergence behavior. The results are validated and compared with available results in literature. The paper explores the relationship between the stochastic wind power and cost of a CHP-wind system. The selection of probability and shape factor for wind availability prediction play an important role in designing and planning a combined wind-CHP generating plant.

TABLE VI. COMPARISON OF COST

	k=1.5				k=2.0				k=2.5			
P_a	0.25	0.3	0.35	0.45	0.25	0.3	0.35	0.45	0.25	0.3	0.35	0.45
Proposed Method	7179.3	7086.4	6994.2	6806.5	7030.5	6947.6	6867.6	6711.5	6933.4	6859.1	6790.1	6657.4
[3]	7179	7087	6994	6807	7031	6948	6868	6712	6933	6860	6790	6658

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